COMMENTARY

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Near-Body Intelligence for Next Generation: Textiles Integrating Personal Thermal Management and Flexible Sensing

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Human survival and health are facing severe challenges from extreme climate change and resource shortages. IEA report indicates that the global average temperature has risen by 1.5 °C compared to the pre-industrial level.[1] Adapting the human body to hot and extreme climates is one of the major challenges to survival and health. Textile-based thermos-functional materials serve as an effective means for personal thermal management (PTM), shifting focus from the entire space to localized microenvironments. PTM technology can produce energy-saving potentials, as increasing building setpoint temperature by 2.8 °C can reduce cooling energy by 29%.[2] Radiative cooling (RC) is a typical technology of PTM. RC materials have the properties of high emissivity at the atmospheric window waveband (8-13μm), and high reflectivity at the solar wavelength band (0.25-2.5μm). Thus, it can effectively transmit the body's heat production and reduce heat absorption to achieve a lower perceived temperature.

However, the prerequisite for thermoregulation is understanding the demands of the human body in real time. The lightweight and flexible nature of flexible electronics enables their integration into textiles, allowing for long-term, continuous, and non-invasive monitoring of physiological signals. The combination of the two heralds a major future trend: integrating PTM and flexible sensing to achieve novel intelligent agents with high perception and strong adaptability.

Then, artificial intelligence (AI) algorithms can help in processing the monitoring data, controlling and evaluating the PTM and flexible sensor technologies. If RC drives the transformation of thermal management technology from environment to human body, then flexible sensing realizes the shift from basic PTM to adaptive PTM. It's assumed that the integration of PTM and flexible sensors could revolutionize the paradigm of smart textiles for maintaining human health and comfort.

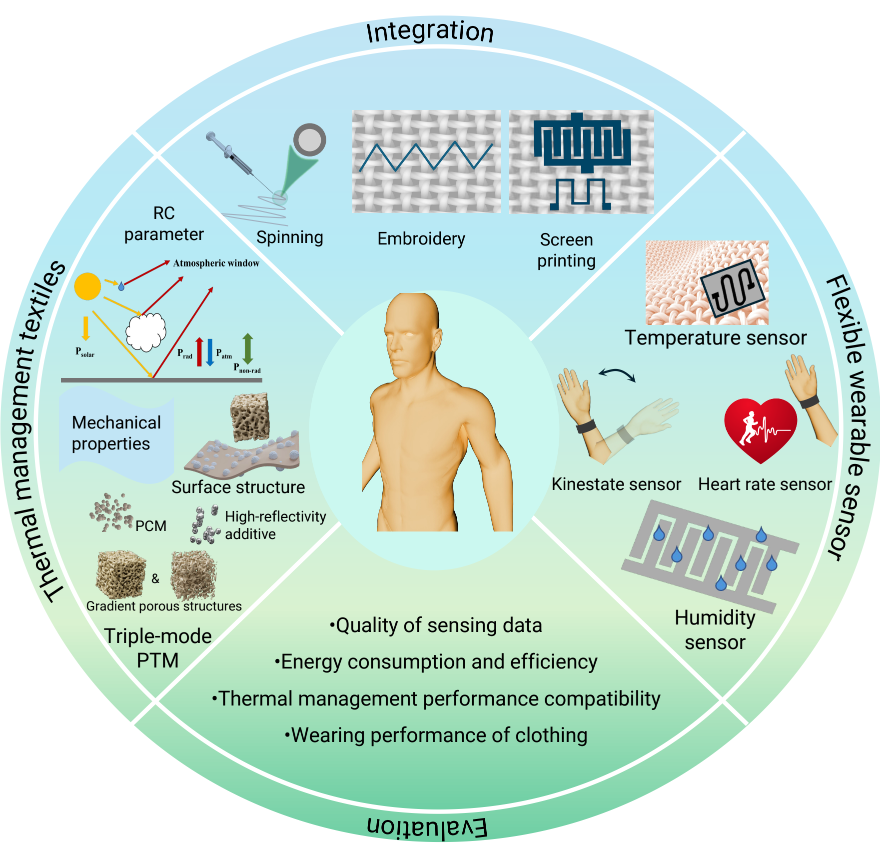

Figure 1. Personal thermal management and flexible sensing and their integration and evaluation

LATEST DEVELOPMENT OF THERMAL MANAGEMENT TEXTILES

The most prominent advantages of PTM textiles are passive energy-free cooling and unrestricted movement freedom. Current research progress of PTM textiles mainly focuses on the following aspects, as shown in Figure 1.

(1) The optimization of the parameters of the thermal management material lies in three perspectives: optimizing the RC infrared emissivity and solar reflectivity to enhance the net cooling power; combining RC with phase change material (PCM) of appropriate temperature for longer-lasting cooling; and balancing the thermal conductivity of the textile to regulate the heat transfer capacity and time of PTM. Further tests and experiments are required to determine the optimal balance.

(2) Novel surface structures can increase the infrared emissivity and solar reflectivity, in which porous, photonic crystal, metamaterials,

multilayer optical film, and biomimetic structures are commonly studied.

(3) Mechanical properties such as strength, toughness and fatigue strength are important in PTM textiles utilization. Selecting fiber substrates with inherently superior mechanical properties is fundamental. Spinning techniques like coaxial electrospinning, optimized loading processes for RC materials, and PCM encapsulation technologies such as phase-change capsules can also enhance stability and durability.

(4) Coupling multiple cooling or insulation principles, such as RC, PCM and asymmetric heat conduction, to prepare dual-mode or triple-mode materials can yield textiles with superimposed cooling effects. Another composite material way is the Janus textiles prepared through multilayer structures or coating methods, which are capable of heating, cooling and moisture management. These textiles can switch between functions via simple flipping or advanced shape-memory metal actuation.

The future breakthroughs will lie in further enhancing the thermal properties of materials, developing multifunctional composite materials, and achieving controllable dynamic responses that can adapt to human demands.

ADVANCED SENSORS FOR INTEGRATED SMART TEXTILES

The integration of thermal management textiles and flexible sensors has pointed out a novel direction for personalized electronic textiles (e-textiles). Precise real-time monitoring by sensors and feedback regulation of key physiological and environmental parameters, such as heart rate, metabolic rate, temperature, and humidity, are required. As shown in Figure 1, heart rate and metabolic rate are crucial indices of health assessment, while temperature and humidity are the indicators for regulating body temperature and sweating. When human activities occur, heart rate increases, metabolic heat production rises, causing an increase in skin temperature and sweating, which further leads to differences in thermal perception. The parameters obtained by sensors represent the integrated whole of organic synergy. Therefore, clarifying the intrinsic mutual influences among the four indicators is significant for e-textiles development.[3]

AI algorithm is an important supporting character in analyzing multi-source data to optimize targets such as thermal comfort and low energy consumption. The dynamic interactive model needs to be explored based on machine learning algorithms,[4] thus to create a collaborative closed-loop system of monitoring, analysis, regulation, and feedback.

INTEGRATION OF INTELLIGENT FLEXIBLE TEXTILES

Textiles are precisely the ideal carriers for flexible sensors. On one hand, the sensors provide intelligent feedback which can regulate the textiles; on the other hand, the heat generated during sensors' operation can be dissipated by thermal management textile. The crucial point in integrating e-textiles is how to load microelectronic components onto textiles or fibers without compromising the cooling effect. PCM-based integration imposes minimal requirements on textile surface properties, whereas RC-based sensor integration depends on the compatibility of optical materials and conductive materials. There are four primary methods for integrating sensing capabilities into textiles[5] as follows, and are illustrated in Figure 1.

(1) Traditional methods, such as pasting and embroidery, are easy to implement but with low reliability and integration, which may also affect the optical properties of RC-based textiles. They are suitable for small-scale integration.

(2) Forming conductive layers on textile surfaces via coating, printing, or 3D printing is suitable for mass production, which can achieve high precision but suffers from poor durability and may affect the RC optical properties. One way is to prepare a double-layer textile by impregnating the RC material on one side and the sensing material on the other side.

(3) Directly loading functional materials onto the textile's surface through vapor deposition and electrostatic self-assembly can create robust and durable circuits. While it also affects RC optical properties and the complex process is suitable for scenarios requiring long-term stable signal monitoring.

(4) Preparing integrated sensing fibers by doping active materials like graphene into spinning precursor solutions. This method offers comfort and durability but features complex processes and high application difficulty. The impact of active materials on RC emissivity and reflectivity should be evaluated first.

SYNTHETIC EVALUATION SYSTEM FOR SMART TEXTILE

E-textiles have received extensive attention in the industry and have extremely high development prospects in thermal comfort and energy conservation. However, a synthetic evaluation system has not yet been obtained from multiple dimensions. The following aspects need to be considered in the establishment of e-textile evaluation.

(1) Thermal management performance compatibility: The integrated sensor should have little impact on the textile cooling capacity, which can be verified by parameter characterization tests and thermal comfort experiments. Thermal performance and thermal comfort indicators include thermal properties like insulation, conductivity, efficiency; subjective feedback like thermal sensation, thermal comfort; and physiological parameters like skin and core temperature, skin wetness.

(2) Energy consumption and efficiency: Sensors are equipped with low-power consumption sensing devices and batteries with lighter weight and higher energy storage density. The relevant volume, mass, electrical efficiency, and operating duration should be considered. Furthermore, it needs to rethink the overall energy utilization of the e-textile, including thermal energy, electrical energy, and the synthetic effects and efficiency.

(3) Quality of sensing data: The sensitivity, accuracy, and reliability of data collected by sensors are significant, as well as the stability of signals under different conditions. Also, the strategy of thermal regulation based on AI model should have repeated iterations, learning and verification.

(4) Wearing performance of clothing: e-textiles should be soft, breathable and lightweight, with good durability, such as wear resistance and washability. It can be evaluated in accordance with relevant recognized standards for clothing.

CONCLUTION

In the future, the development of PTM and flexible sensing will expand from physical coexistence to information symbiosis. Clothing will no longer be a passive cover for the human body, but the "second skin" at the human-environment interface, which has both functionality and subjective capabilities. It can provide the human body with strong adaptability in extreme climates. Furthermore, it is developing towards the wearable intelligent agents with the ability to monitor and regulate physiological indicators and micro-environments in real time based on intelligent sensing and AI. This paradigm shift requires in-depth intersections among research fields such as materials, energy, electronics, and physiology. We call for the formulation of relevant standards for wearable e-textiles and the establishment of a database and cloud platform for multi-dimensional human monitoring. It not only reflects the standardized and unified evaluation of functionality, but also pays attention to the differentiated demands of individuals, which promotes the advancement of this field from functional demonstration to long-term wearables. In this way, we aim to provide every individual a "private climate" in the era of climate crisis, enhance their ability to cope with shocks, and achieve effective protection of human life and health.

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DECLARATION OF INTERESTS

The authors declare no competing interests.